Real-Time Robotic Surveying for Unexplored Arctic Terrain

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***Abstract*—Global warming and the resultant change occurring in the mass of the Earth's ice cover has spawned a new interest in determining how robotic technology can be leveraged to measure such change. The concept of a robotic survey system has emerged, intended to facilitate the collection of ground-based information as validation of that collected by satellite-based instruments. Currently, the only publicly available methods for *in situ* measurements are stationary automatic weather stations (AWS), limited in sensing range, expensive aerial campaigns, and dangerous human-led field expeditions. Robotic surveying has been defined for varying applications in both domains of theory and practice, demonstrating the potential in extending its usage to this area of field robotics, specifically NASA Earth Science missions. Based upon the 2007 Decadal Survey, programs like DESDynI, GRACE-II and ICESat-II are the most relevant with the potential to support other missions whose locales of interest are both navigable and support a deploy-able system. This application of robotics expands the potential for improvements to acquired information by remote-sensing methods. We present a review of robotic surveying and its relevance to enhancing the capabilities of current NASA Earth Science missions.**

***Index Terms*—Automatic weather stations (AWS), Earth Observing System (EOS), line of sight (LOS)**

I. Introduction

The development of an Earth-Observing System (EOS) requires the input of multiple scene perspectives at varying resolutions to quantitatively measure various aspects of global climate change. Our focus is on improving one such perspective by developing *in situ* methods which yield the greatest ratio of information gain to resource usage. These resources can typically be modeled as operating costs incurred for the given technique specified. In this work, the issue of resource allocation is redefined in the context of a robotic solution which aims to augment currently existing resources and add fidelity to information used by an EOS.

A. Motivation

Geophysical studies reveal that over the past twenty years, the cause of an increase in global sea level can be inferred from continual decreases in the mass of the Earth's ice cover [1–4]. These reports are often based on detailed comparisons of digital elevation map (DEM) information acquired from remote sensing data of large areas (e.g. > 100 km^2) [1]. Though this data is efficiently processed, the available resolution that it can provide comes attached with error bounds and spatial limitations that must be accounted for during image processing [1]. Typically, a single pixel of an acquired DEM image can provide an average elevation measurement representative between 100 – 900 m^2 of terrain and ± 7 – ± 15 m of error [5]. Even higher resolution imagery is possible (9 m^2 @ ± 1 m error), yet availability of such information is often limited to specific areas and dependent upon satellite mission objectives. While this is useful for imaging the entire Earth, more information at the sub-pixel level is advantageous for studying climate change within focused regions. It is for this reason that the use of an *in situ* solution as a tool to view these locations is appropriate. As an example, the imagery available from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument provides resolutions for areas as small as 62500 m^2. Higher resolutions are available with alternative equipment, yet, there exists a trade-off with available wide-area coverage. This establishes our motivation to provide Earth scientists with a more accurate assessment of slope found within remote satellite imagery at the sub-pixel level.

B. Land Surveying

Within both urban and rural areas, land surveying is a technique used by architects, civil engineers and other types of city planners to "measure the relative positions of existing objects" [6]. More specifically, topological surveys can reveal important non-deterministic features of a terrain, such as its change in slope, that are otherwise unquantifiable at small spatial scales by remote satellites. The focal point of this research is to apply surveying to a multi-agent robot system such that it will explorer terrain at the desired scale and reveal previously unattainable detail therein. The concept of two dynamically coordinating agents exploring terrain according to surveying principles while collecting relevant science data is a significant contribution to the Earth Science missions at large.

C. Relevance

The improved characterization of natural features such as slope from the Arctic and analogous environments is an increasingly relevant application for NASA's Climate Variability and Change research division. As global warming continues to incite irregular weather patterns worldwide, sea levels continue to rise due to accelerated glacial melt. When considering these changes, detecting the features found in these environments will require a robust sensing system capable of intelligently combining current sensing practices with integrated autonomy. In contrast to performing more qualitative assessments to explain changes occuring throughout various glacial regions

[3], the increase in information gain afforded by our system will enable opportunities for improved quanitative assessments at finer resolutions. Utilizing robust mobile sensors, this paper presents a system influenced by the principles of land surveying to address the need for these improved assessment methods.

II. Potential Applications

Based upon recommendations of the 2007 NASA Decadal Survey, this work is most beneficial to any mission's primary or secondary objectives involving the measurement of changes in topography, specifically that found in the Arctic. The projects identified here are a sampling from a larger list of missions (6 in total) whose aim is to produce valid climate predictions based on improved measurement of ocean temperature and ice sheet volume dynamics [7]. This encompasses missions such as Deformation, Ecosystem Structure, and Dynamics of Ice (DESDynI), the Gravity Recovery and Climate Experiment (GRACE-II) and Ice, Cloud, and land Elevation Satellite (ICESat-II). These three specifically pose relevance to this research, requiring remote monitoring of the Arctic and Arctic-like regions where our robotic system is designed to operate.

A. Proposed Projects

The DESDynI project investigates the response of ice sheets to climate change and its impact on sea levels. Relying on L-Band Synthetic Aperture Radar (SAR) and multiple-beam lidar in the infrared spectrum, extremely low error tolerances are achieved (on the order of 1 [m]).

GRACE seeks to measure the mass distribution of the Earth and its spatio-temporal flucuations as a function of water motion across the globe. It relies on a measurement of time variations in the Earth's gravity field to detect these changes in mass, a quantity directly impacted by rapid melt of large glacial regions. The second installment of this project (GRACE-II) focuses on the quantities of groundwater storage at spatial resolutions that will provide insight for improving current weather and climate model estimates. The broader impact of the work is to improve resource management for water storage in underdeveloped countries.

ICESAT-II carries on the mission from the original ICESAT, determining the contribution of global sea level to changes in terrestrial ice cover. The shape of ice sheets is the primary indication of their changing behavior and therefore requires effecient altimetry. It is proposed that measurements combined from the single-channel lidar of ICESAT-II, the gravity system of GRACE-II and the SAR system of DESDynI will produce a useful point of analysis for predicting future changes in land and sea ice cover.

Regardless of the extensive amount of remotely captured data from these three proposed systems, the limitations of the technology induce inherent error bounds on measurements acquired. For this reason, *in situ* solutions must be employed to highlight detail that is otherwise unattainable and incorporate this high resolution information into the modeling process responsible for producing its associated imagery (Fig. 1).

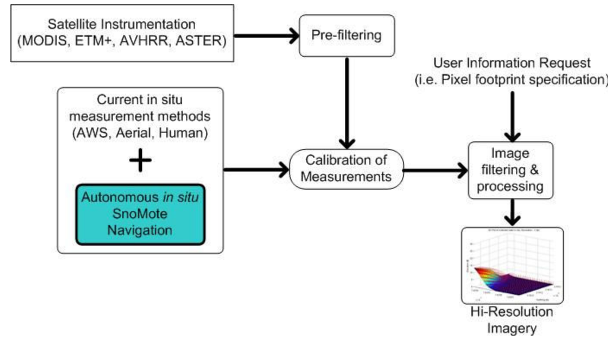

Fig. 1. High-level flowchart for incorporating new $in\ situ$ data

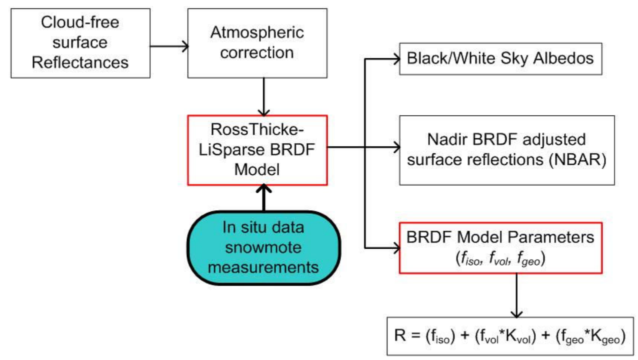

Fig. 2. Flowchart describing albedo measurement processing with proposed improvement

B. Example Application: MODIS and Albedo

The processes of measuring surface albedo typically encompasses acquiring irradiant energy measurements from various remote satellite equipment at multiple bandwidths. One such set of related projects conducts studies of the MODIS instrument. On a continual basis, image processing algorithms that account for different atmospheric effects are applied to information collected from MODIS, coordinating its arrangement into relavent imagery representative of the areas of interest [8]. According to [9], even with the use of AWS networks as the source of *in situ* measurements, there exists an unquantifiable amount of error that can only be remedied by sampling at multiple spatial scales. It is in the midst of this processing that terrain data captured by our robotic survey system is most relevant, enabling the acquisition of this detail, scalable to a scientists' particular needs. Specifically, this information can serve as input to a Bi-directional reflectance distribution model (BRDF) commonly employed to generate the necessary reflection information of an area under investigation (Fig. 2) [10].

The complexity varies, however, it is believed that adjustments can be made to the closed-form solutions defining these models (see [8]) by including new parameters derived from the information obtained using our survey system.

III. Surveying for Earth Science

Most topographical maps are usually derived from remote sensing equipment, relying on custom on-the-ground techniques to validate the accuracy of these measurements [11]. The most current solutions for obtaining *in situ* measurements for Earth science applications such as this include AWS networks, aerial coverage by commercial or private planes, or human-led expeditions. As mentioned earlier, each of these options carries with it drawbacks that would be mitigated significantly with a low-cost robotic surveying system [12]. By applying the concept of land surveying to robotics, we have developed a fourth viable alternative for extracting relevant detail in areas of interest within the pixel footprint of remote imagery.

A. General Surveying Principles

Among other descriptions, land surveys are defined as the type which *"...are made for the purpose of representing the three-dimensional relations of the Earth's surface on maps or models. The features shown include such natural objects as streams, lakes, timber, relief of the ground surface, etc. "* [13].

Surveying encompasses many sub-categories including land, route, city/municipal, etc. It is the area of topographical surveying with which we focus our efforts. The art of topographical surveying requires two points of reference with a line of sight (LOS) and whose geographical positions change incrementally. Concurrently, it is expected that the associated changes in the slope of each LOS distance are carefully documented such that elevations can be measured at specific $control\ points$. These control points are either managed as a collection of locations within a pre-specified grid or arbitrarily chosen by a certified human surveyor. Typically, this topographical surveying incorporates two distinct roles, an $Instrumentman$ and a $Rodman$. Both the Instrumentman and Rodman must coordinate with each other to obtain the desired distance and angular measurements during a survey. Furthermore, these measurements must be sufficient for estimating a contour map *posteriori*. The Instrumentman is identified as being responsible for recording the precise bearing and distance from their location to that of the Rodman. The role of the Rodman is more flexible in that, they must serve as a reference point from which the Instrumentman must measure. There are any number of designated pieces of surveying equipment or methods used to accomplish this two-person task including pacing, odometer, taping, stadia or most recently, electronic distance measurment tools (EDM) [14].

This is a field which dates back centries, yet has always relied on humans, only recently resorting to newer technology (i.e. electronic tape measures, automatic logging equipment) to supplement the tedious aspects of the craft. Additionally, there has been little progress in the adoption of a common navigation methodology for performing small-scale land surveys (areas $<$ 62500 m^2), let alone for areas critical to Earth Science missions. By harnessing the capabilities of a robotic survey system equipped with a certain measure of autonomy, a new paradigm can be developed for ice sheet study and other science-driven exploration missions.

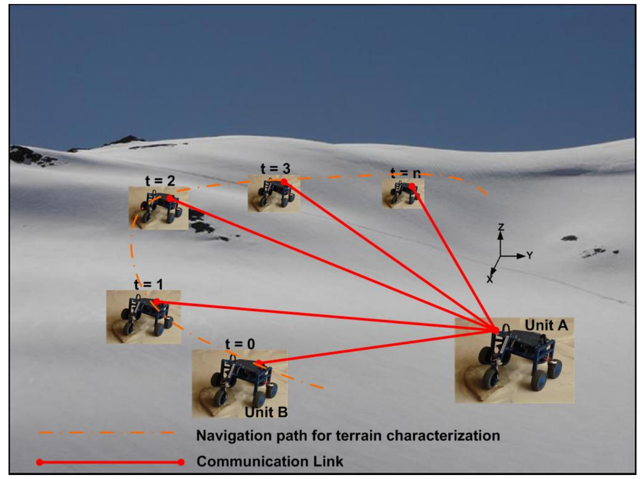

Fig. 3. Robotic surveyor system concept

B. Robotic Alternative

This work builds upon previous advances in cooperative robotics in two ways: 1) by considering a dynamically changing distance relationship between agents, emphasizing communication to affect navigation decisions online and 2) by incorporating tilt sensing and LOS to extract relavent elevation and slope information from a real 3D environment. These features are derived from the fundamentals of land surveying techniques, leveraging this common trade to increase the amount of knowledge about an area. Since no robotic system is totally autonomous and void of external monitoring, we seek to accomplish these surveying tasks $with$ human presence but $without$ human dependence.

1) Previous Robotic Work: As early as 2001, the study of cooperative teams of robots has been considered an innovative way of addressing the search/coverage problem [15–18]. Typically, the success of these approaches is measured in terms of $Quality\ of\ Performance$, QoP. This metric is defined as the ratio of an area of interest to the total distance travelled during the search (Eqn. 1). These studies are driven by scanning paradigms whereby a constant distance relationship between two agents is defined for the duration of the task. This allows joint search soley for the purpose of locating objects, large or small, depending on the size of the search space. Previous research also presumes that these searches are executed in a relatively flat environment. Since these assumptions are impractical for a 3D real-world implementation, we make improvements to this work by incorporating principles of surveying. Eventually, our techniques will include the QoP as a post-analysis metric for evaluation, but it will not drive our algorithm development.

$$QoP = A_s/D_s \tag{1}$$

- QoP: Quality of performance
- A_s: Total area surveyed
- D_s: Total distance traveled by survey system

Other robotic solutions specifically designed for navigation in the Arctic include the CoolRobot from Dartmouth College,

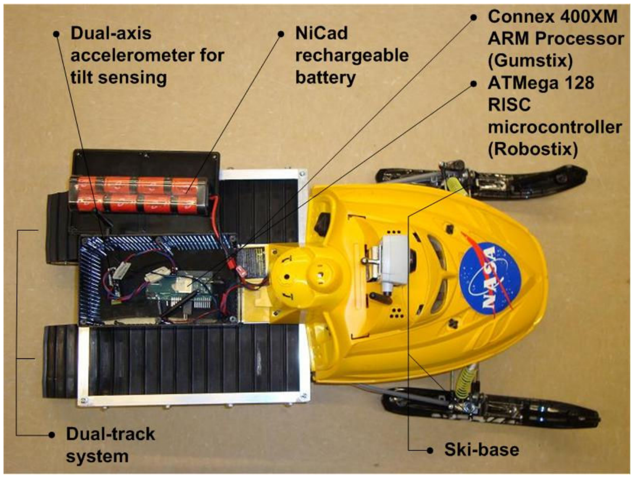

Fig. 4. Breakout diagram of a SnoMote platform

the Nomad project from Carnegie Mellon University, and MARVIN out of the University of Kansas [19–23]. With respect to meeting the needs of a robotic survey system, each of these is lacking in either the capability to negotiate 3D terrain or requires too restrictive a dependence on human-teleoperation for successful naviation [24].

2) The SnoMote Platform: Inspired by the traditional structure of a snomobile, the SnoMote platform (Fig. 4) accounts for the stability and steering capabilities demanded for navigation in environments like the Arctic and has successfully been tested on glaciers in Juneau, AK. More detail on its operation and mechanical design is found in [10; 12; 24; 25]. With the exception of extremely harsh weather conditions, our system is capable of operating in the field for extended periods of time, periodically recharging, and continuing to collect measurement data. In contrast to the aforementioned work in III-B1, this light-weight mobile sensing solution provides the most robust option with which to implement a dual-agent robotic surveyor.

IV. Conclusions and Future Work

Using these autonomous agents in this way addresses coverage, cost and safety issues. While networks of AWS units exist, they are limited by their immobility. Currently, some of these units are no longer functional, buried within the ice cover due to excessive snow fall, rendering them irretrievable and unable to provide useful data to an EOS. In contrast to airborne expeditions, these campaigns are restrictive in the amount of fuel and the number of passes they are able to make during a single run over a specified area. Additionally, the costs and complex post-processing required for the multiple modes of sensing is astronomical compared to our COTS robotic platform. Finally, the inherent element of safety makes a multi-agent robotic system more appealing by reducing the number of scientists needed to conduct field tests. Should one or both agents be lost or damaged beyond repair during testing, this setback is minimal when compared to the risking of human life.

The algorithms planned for development provide the system with behaviors that are modeled after topographical surveying practices. Certain boundary information is presumed to be known, as with humans performing a land survey, yet, the decisions made by both robotic units are more dynamic. The system, as a whole, will maintain a high-level goal of minimizing the total distance traversed while maximizing collection of the most interestingly detailed portions of the area under test. The raw sensor data collected during future field tests with the SnoMotes in a surveyor configuration will be presented to confirm the hardware system realized from extensive simulation. As the system is improved upon to perform in simple environments (e.g. sporadically placed hills and valleys), more complex scenarios will be tested in simulation using a custom MATLAB digital elevation map (DEM) creator. This will enable the simulation of uneven features that are more closely tied to a realistic environment, i.e. Arctic, Moon, Mars, etc.

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